CARBON FOOTPRINT OF ENGINEERED WOOD PRODUCTS: A REVIEW OF PRODUCTION EMISSIONS AND INFLUENCING FACTORS

Yi Qian[1], Tharaka Gunawardena [2], Priyan Mendis [3], Lu Aye[4]

ABSTRACT: Engineered wood products (EWPs) play a critical role in decarbonising the built environment. However, the carbon footprint of EWPs varies widely due to inconsistencies in data sources, system boundaries, and modelling approaches. This paper reviews 63 publications and reports to identify carbon emissions associated with the production stages (A1–A3) of EWPs, with a focus on regional trends, data transparency, and methodological consistency. We find that emission values range significantly - from 29.7 to 840 kg CO_2-eq m^{-3} depending on location, product type, and modelling assumptions. Key influencing factors include biogenic carbon accounting, use of dynamic life cycle assessment, and the treatment of forestry residues. The paper calls for harmonised methods and improved inventory datasets to support reliable carbon accounting in timber construction.

KEYWORDS: Engineered Wood Products, Carbon Footprint, Production Stage, Life Cycle Assessment, Forestry Emissions

1 – INTRODUCTION

The global building sector accounts for nearly 39% of annual greenhouse gas emissions, prompting urgent efforts to decarbonise construction materials. Among various alternatives, engineered wood products (EWPs) have gained attention due to their lower embodied carbon and ability to store biogenic carbon. These products are increasingly promoted as climate-friendly alternatives in green building certification systems and national low-carbon strategies. Yet, the accuracy and comparability of their carbon footprints depend heavily on the data sources, system boundaries, and accounting methods used. However, carbon footprint estimates for EWP production stages (A1–A3) remain inconsistent across studies, making it difficult to compare results or guide policy. This paper critically reviews current literature on EWP production emissions, aiming to identify the key drivers of variation, assess regional trends, and highlight methodological differences. A particular emphasis is placed on emission factors, biogenic carbon accounting, and the role of life cycle assessment (LCA) approaches in shaping reported values.

2 – KEY STANDARDS, METHODS, AND APPLICATIONS OF CARBON ACCOUNTING

2.1 CARBON ACCOUNTING STANDARDS AND GUIDELINES

The evolution of carbon accounting standards has led to a diverse set of frameworks targeting GHG emissions at different levels - product, organisational, and sectoral. Foundational standards such as ISO 14040 and ISO 14044 establish the core principles of LCA, upon which more specialised guidelines have been developed. At the product level, ISO 14067 and PAS 2050 provide methodologies for calculating the carbon footprint of products using LCA principles, while EN 15804 adapts these for Environmental Product Declarations (EPDs) in the construction sector.

At the organisational scale, the GHG Protocol Corporate Standard and ISO 14064-1 guide emissions reporting, including value chain emissions under the GHG Protocol Scope 3. The EU Organisation Environmental Footprint (OEF) advances these approaches further by offering

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https://doi.org/10.52202/080513-0588

harmonised guidance for environmental reporting across European industries. At the sectoral level, the IPCC Guidelines are used globally for national GHG inventories and provide structured methods to account for biogenic carbon stocks and fluxes in harvested wood products (HWPs).

As illustrated in Figure 1, these standards are highly interconnected. Later frameworks often build on earlier methodologies - for example, PAS 2050 draws from ISO 14044, and the GHG Protocol Product Standard aligns closely with ISO 14067. Despite this common foundation, significant variation arises due to differences in system boundaries, allocation methods, and the treatment of biogenic carbon.

These methodological choices have a measurable impact. Garcia & Freire (2014) reported a carbon footprint range from -939 to 188 kg CO2-eq m^{-3} for particleboard when applying different standards [1]. Peter et al. (2016) showed the IPCC Tier 1 method could overestimate emissions compared to Tier 2 [2]. A central challenge in timber carbon accounting is the inconsistent treatment of biogenic carbon. While PAS 2050 assigns credits based on a 100-year average carbon storage time, ISO 14067 defines forest carbon uptake as a negative emission and requires inclusion of land-use change impacts. These discrepancies affect long-term carbon balance estimates and can influence material comparisons and claims.

Several broader issues also limit consistency across frameworks. Dye et al. (2024) point to the complexity of forestry operations, annual variability in emissions, and difficulties in capturing disturbances such as fires or pest outbreaks [3]. Furthermore, differences between international systems, such as the UNFCCC's approach to carbon ownership versus the SEEA's classification of carbon sequestration as an ecosystem service, introduce ambiguity. For timber products, this creates uncertainty in how carbon storage is reported and valued, which affecting market signals, policy incentives, and environmental claims.

In light of these challenges, there is a growing need for harmonised and timber-specific carbon accounting frameworks that can account for forestry dynamics, long-term storage, and regional variations with greater accuracy and transparency.

2.2 CARBON ACCOUNTING METHODS

LCA is a widely accepted approach for assessing the environmental performance of timber products across their life cycle. It supports cradle-to-gate or cradle-to-grave assessments and can be implemented through several modelling approaches. Process-based LCA relies on detailed, site-specific inventory data and forms the basis for most EPDs. Input-output (IO) LCA, in contrast, uses national economic accounts to estimate emissions across upstream and downstream supply chains. Hybrid LCA combines both approaches, seeking to maintain process-level accuracy while broadening the system boundary. Dynamic LCA introduces a temporal dimension to the modelling of emissions and carbon storage, which is particularly relevant for timber products with long service lives. Recent studies have illustrated the significance of method choice. Lausselet et al. (2022) found that timber's contribution to total embodied emissions increased from 24% under process-based LCA to 40% using hybrid LCA, due to the inclusion of indirect emissions [4]. Peñaloza et al. (2016) demonstrated that applying dynamic LCA to a four-storey CLT building reduced reported emissions by 10–22% compared to static LCA, depending on the assessment time horizon [5].

MFA is another valuable method for carbon accounting in the forestry and timber sectors. It tracks the flow of materials and associated carbon stocks through defined systems, providing a mass-balance perspective that complements LCA and IPCC-based models. MFA can be conducted as either static or dynamic modelling. Static MFA evaluates material flows at a specific time or life cycle stage, while dynamic MFA tracks changes in carbon stocks over time, reflecting shifts in product use, recycling, and waste treatment. For instance, Bergeron (2016) applied static MFA to simulate wood flows in Switzerland and found that energy recovery from waste wood could reduce national CO_2 emissions by 364 tonnes annually [6]. Wang and Haller (2024) used dynamic MFA to analyse wood flows in Germany between 1991 and 2020, showing that carbon emissions peaked during storm years and highlighting the long-term carbon storage potential of wood use in the construction sector [7].

Each of these methods relies on emission factors (EFs) to convert activity data into GHG emissions. Different carbon accounting methods apply EFs in distinct ways (see Eq. (**Error! Reference source not found.**), (**Error! Reference source not found.**), and (**Error! Reference source not found.**) for IPCC, LCA, and MFA methods, respectively). The IPCC method uses a simple multiplication of activity data by an EF, while LCA aggregates emissions across life cycle stages by summing the product of mass and EF for each stage. MFA similarly applies EFs to each quantified material flow. While the structure of these equations may appear consistent, the assumptions underlying them, such as decay rates, energy sources, and system boundaries - can yield substantially different results. As such, selecting the appropriate method and aligning it with the intended application is crucial for transparent and meaningful carbon accounting in timber construction.

IPCC methods:

$$E = AD \times EF \quad (1)$$

where:

E: Emissions, kg CO_{2eq}, (e.g., GHG emissions from timber products);

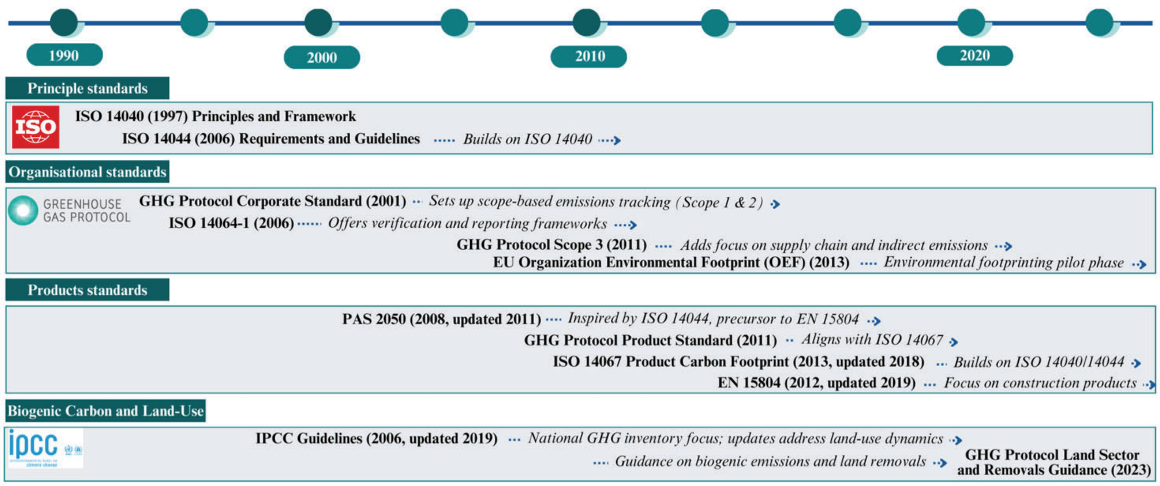

Fig. 1. Evolution of carbon accounting standards and guidelines for timber buildings and EWPs (italics indicate the interconnectivity))

AD: Activity data, kg or m^{-3}, the quantity of timber or wood product at each lifecycle stage (e.g., harvested timber, wood processed for construction);

EF: Emission factor, kg CO_2eq kg^{-1} or kg CO_2eq m^{-3}, represents the GHG emissions per unit of activity (e.g., per cubic meter of timber). It can be default (Tier 1 and Tier 2) or adjusted (Tier 3)

LCA method (process-based):

$$E = \sum_{i=1}^{n} (M_i . EF_i) \quad (2)$$

where:

n: Number of life cycle stages;

E: Emissions, kg CO_{2eq}, total emissions from the timber product's life cycle;

M_i: Mass or quantity of timber used in 'i' life cycle stage, kg, (e.g., processing, transport, disposal);

EF_i: Emission factor for the 'i' life cycle stage, kg CO_2eq kg^{-1} or kg CO_2eq m^{-3}, (e.g., processing, transport, disposal)

MFA method (static MFA):

$$E = \sum_{i=1}^{n} (MF_i . EF_i) \quad (3)$$

where:

E: Emissions, kg CO_{2eq}, total emissions from the timber product's life cycle;

MF_i: Material flow for each stage (e.g., harvested timber, processed wood, waste wood) through the system;

EF_i: Emission factor associated with the material flow at each stage, kg CO_2eq kg^{-1} or kg CO_2eq m^{-3}, it can include carbon emission, carbon sequestration, waste wood treatment impacts, etc.

The methods are interconnected. For instance, the IPCC Tiered Approach leverages LCA and MFA to improve accuracy. MFA often enhances carbon storage estimates, as shown in a Czech study where Tier 3 methods using MFA estimated carbon inflow in EWPs 15.8% higher than Tier 2 [8].

3 – Methodology

This study adopts a systematic review approach to identify and analyse peer-reviewed literature and industry reports on carbon accounting for timber buildings and EWPs, with a specific focus on the production stage (A1–A3). Following the protocol outlined by Siddaway et al. (2019), relevant studies were sourced from two major academic databases: ScienceDirect and Web of Science Core Collection [9]. The search strategy employed a combination of keywords related to "timber," "engineered wood products," "carbon footprint," "life cycle assessment," and "emission factors," among others.

The review was limited to publications between 2014 and 2025 to ensure the inclusion of the most recent methodological advancements and sectoral practices. A total of 1,205 articles were initially retrieved. After applying predefined screening and eligibility criteria - including relevance to timber construction, carbon quantification at the product level, and methodological transparency - the dataset was refined to 51 peer-reviewed papers. In addition, 12 EPDs were manually selected for their technical depth and compatibility with the review objectives, bringing the total number of analysed sources to 63. The full screening process and inclusion logic are summarised in Figure 2.

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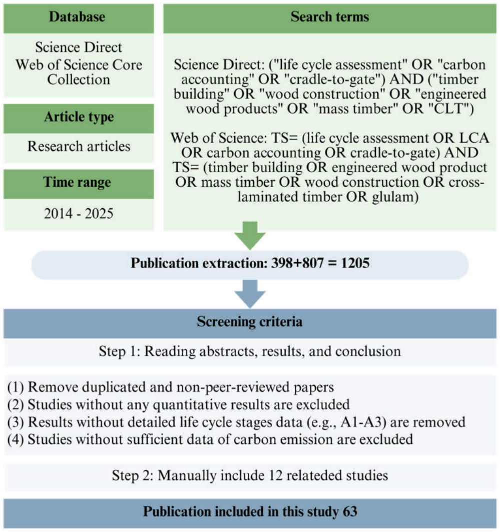

Fig. 2. Review process of this study

4 – RESULTS

4.1 RESEARCH TRENDS AND THEMATIC FOCUS

To understand the evolution of research on carbon accounting in timber construction, a keyword co-occurrence analysis was conducted. Figure 3 presents the clustered map of frequently appearing terms across the reviewed literature between 2014 and 2025. Four dominant research clusters emerge, centred on life cycle assessment, carbon emissions, engineered wood products, and timber buildings. This indicates a growing convergence of interest in integrating biogenic carbon flows and methodological consistency into construction-related carbon modelling.

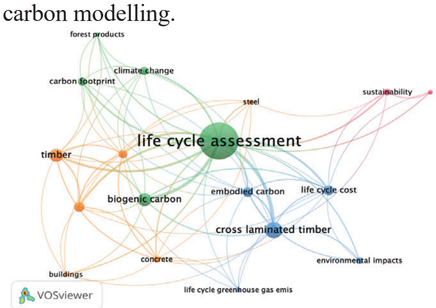

Fig. 3. Keywords co-occurrence cluster map form 2014-2025

4.2 SYSTEM BOUNDARIES AND FUNCTIONAL UNITS

System boundary selection plays a critical role in shaping LCA results for timber buildings and EWPs. As illustrated in Figure 4, cradle-to-grave boundaries were the most common, applied in 42.9% of all reviewed studies. Among timber building studies, 56% adopted this boundary, often including operational energy (B6) in 60% of cases. Interestingly, end-of-life (C1–C4) and beyond-life-cycle stages (D) were considered more frequently than the full building use phase (B1–B7). In contrast, over half of EWP studies (53%) applied cradle-to-gate boundaries, while 24% adopted cradle-to-grave.

Inconsistencies were found in boundary terminology. For instance, cradle-to-site (A1–A5) was occasionally labelled as Production and Construction (P&C), leading to overlap and ambiguity (e.g.[10], [11]). Similarly, Moncaster et al. (2018) reported cradle-to-site and end-of-life boundaries for a building in the UK [12], while Allan & Phillips (2021) described comparable stages under a cradle-to-grave framework [13]. These inconsistencies underscore the need for clearer and more standardised boundary definitions in timber LCA studies.

As shown in Figure 5, the functional unit varied across timber building studies. Most adopted 1 m² of floor area (35.3%), followed by whole-building metrics (32.4%) and heated floor area (8.8%). Less common units included net floor area per annum and square metre of structural component. For EWPs, the vast majority of studies applied 1 m³ of product, although flooring-related studies used 1 m² to align with installation use cases.

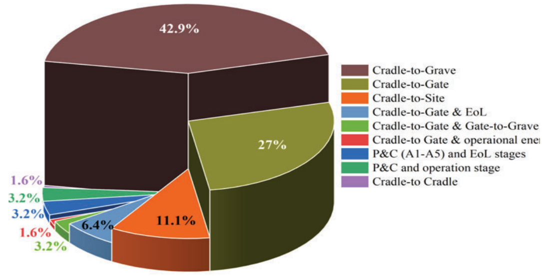

Fig. 4. Distribution of system boundaries across studies

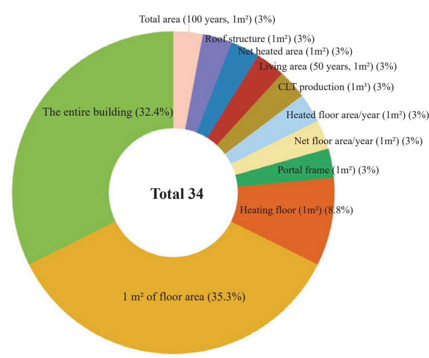

Fig. 5. Functional unit of reviewed timber building cases

4.3 LIFE CYCLE INVENTORY (LCI) DATABASES

LCI databases significantly influence carbon footprint results. As shown in Figure 6, Ecoinvent was the most frequently used source (24.7%), followed by SimaPro

(15.1%) and USLCI (13.7%). Other databases, including GaBi, Athena IE4B, and CORRIM, accounted for 31.4% combined. Notably, some studies cited software (e.g., SimaPro) without specifying the integrated database, creating inconsistencies in reporting.

Approximately 36.5% of studies used multiple data sources, including factory-gathered inventories, national datasets, and expert interviews (e.g., [14], [15]). GaBi was cited in 50% of EPD reports but was rarely referenced in academic papers, revealing a divergence between industrial and academic preferences.

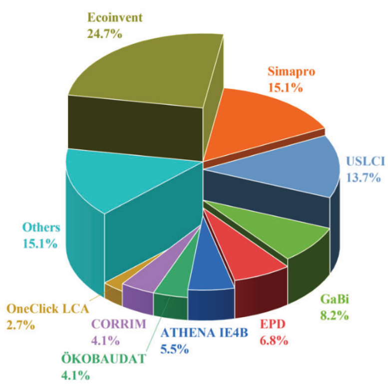

Fig. 6. Distribution of LCI databases used in reviewed studies

4.4 ENGINEERED WOOD PRODUCT CATEGORIES

Among the 63 reviewed articles, 66 EWP cases were identified, with some studies assessing multiple products. As shown in Figure 7, cross-laminated timber (CLT) was the most frequently studied EWP (31.25%), followed by glulam (12.5%), plywood and OSB (15.6%), and a range of niche or emerging products (7.8%). Together, mass timber products (CLT and glulam) accounted for over 40% of all cases, reflecting their increasing use in low- and mid-rise construction.

CLT was also the dominant EWP in timber building assessments, appearing in roughly 80% of such studies, including hybrid variants (e.g., CLT with rock wool or wood fibre). Other EWP studies showed greater diversity, including products like lightweight timber (LWT), MDF, DHF, fibreboard, and LVL. Tree species were generally underreported, except in US-based studies, which most frequently referenced Douglas-fir, loblolly pine, western hemlock, red oak, and white oak.

4.5 CARBON EMISSIONS FROM THE PRODUCTION STAGE

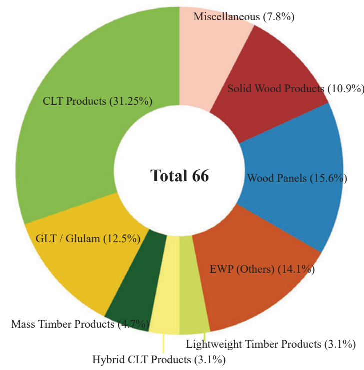

Fig. 7. Distribution of EWP types in the reviewed cases

Table 1. Carbon emissions calculation table for timber-based buildings

	Asia	Europe	North America	Oceania
CF_{med} (kg CO_2eq m^{-2})	190.5	163.9	160.4	319.2
$CF_{25\%}$ (kg CO_2eq m^{-2})	138.3	110.6	145.5	289.4
$CF_{75\%}$ (kg CO_2eq m^{-2})	287.0	330.3	289.4	349.0

CF_{med}, $CF_{25\%}$, $CF_{75\%}$: the median, first quartile, and third quartile of carbon emissions

Table 2. Carbon emissions calculation table for engineered wood panels

	Asia	Europe	North America	Oceania
CF_{med} (kg CO_2eq m^{-3})	139.0	25.2	184.5	118.0
$CF_{25\%}$ (kg CO_2eq m^{-3})	124.5	15.1	162.8	97.8
$CF_{75\%}$ (kg CO_2eq m^{-3})	168.5	38.8	329.8	149.0

CF_{med}, $CF_{25\%}$, $CF_{75\%}$: the median, first quartile, and third quartile of carbon emissions

4.5.1 REGIONAL ANALYSIS

Carbon footprint (CF) values for both timber buildings and EWPs were assessed across regions based on the A1–A3 production stage. Summary statistics (median, 25th and 75th percentiles) are provided in Tables 1 and 2.

For timber buildings, median CF values (kg CO_2-eq m^{-2}) ranged from 160.4 in North America to 319.2 in Oceania. Europe and Asia reported medians of 163.9 and 190.5, respectively. For EWPs, regional medians (kg CO_2-eq m^{-3}) were lowest in Europe (25.2) and highest in North America (184.5), with Asia (139.0) and Oceania (118.0) in between.

As shown in Figures 8 and 9, North America displayed the widest emission range, influenced by variation in electricity sources, resin types, and manufacturing energy intensity. Europe's lower CF values reflect consistent use of low-carbon electricity and stringent LCA standards. Oceania reported the highest building CFs, partially due to higher material substitution with non-timber components such as concrete and steel.

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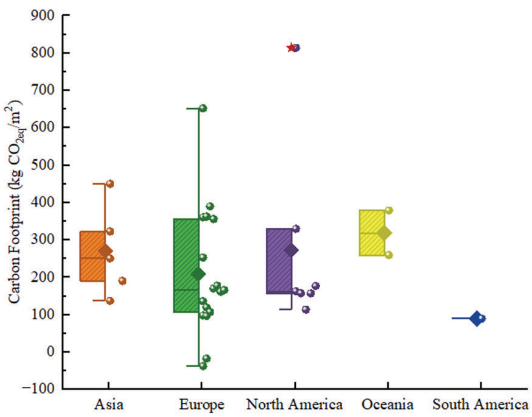

Fig. 8. Regional carbon footprint distribution for timber-based buildings during the production stage (kg CO_2eq m-²) (Outlier marked as red star)

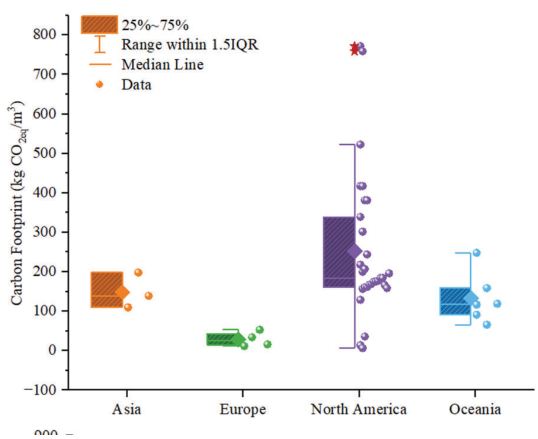

Fig. 9. Regional carbon footprint for engineered wood panels during the production stage (kg CO_2eq m-³) (Outlier marked as red star)

4.5.2 EMISSIONS BY LIFE CYCLE SUBSTAGE (A1–A3)

Figure 10 presents the relative contributions of A1 (raw material extraction), A2 (transport), and A3 (manufacturing) to the total production-stage CF. Median contributions were 50.7% for A1, 12.2% for A2, and 37.1% for A3. A1 stages often dominated due to forestry-related fuel use, with reported ranges from 16.5% to 75% (Júnior & Seixas, 2006). A2 contributions were generally modest due to short transport distances in most case studies. A3 emissions varied significantly (8.8% to 64.5%), depending on adhesive types, drying processes, and energy source mixes.

These results indicate that the production-stage CF of timber materials is highly sensitive to regional energy systems and manufacturing practices, further reinforcing the need for transparent and standardised reporting.

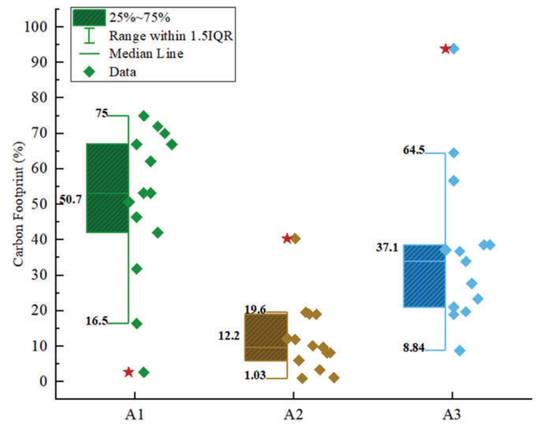

Fig. 10. . Carbon footprint distribution (%) across A1–A3 substages (raw material extraction, transportation, and manufacturing) for timber-based buildings and EWPs. (Outlier marked as red star)

5 - DISCUSSION AND IMPLICATIONS

5.1 SYSTEM BOUNDARIES, FUNCTIONAL UNITS, AND COMPARABILITY

The choice of system boundaries and functional units strongly influences carbon footprint results. While cradle-to-grave boundaries were most common in timber building studies, a significant share of EWP studies adopted cradle-to-gate boundaries, reflecting differing priorities between product- and building-level assessments. Such inconsistencies make comparative analysis challenging. Additionally, functional unit variation—particularly the use of whole-building units in 32.4% of studies—complicates cross-study comparison due to differences in size, function, and design. Standardising units to reflect spatial, temporal, and functional equivalence is essential for meaningful benchmarking.

5.2 DATA QUALITY, DATABASE SELECTION, AND PRODUCT FOCUS

Database choice significantly shaped LCA outcomes. Ecoinvent was the most widely used, but varying use of background datasets (e.g., SimaPro, GaBi, USLCI) introduced discrepancies. Many EPDs lacked transparency on upstream assumptions or excluded beyond-gate stages. Harmonising database reporting and improving EPD traceability are needed to enhance consistency. CLT emerged as the dominant EWP in literature, yet other promising materials like veneer-based mass panels remain under-researched, particularly in emerging timber markets such as Australia.

5.3 EMISSION VARIABILITY AND BIOGENIC CARBON TREATMENT

Large discrepancies in reported emissions were found, even among similar cases. This variation stemmed from data source differences (e.g., database vs. onsite data), regional practices, and inconsistent treatment of biogenic carbon. Some studies reported negative CF values without clearly explaining biogenic carbon allocation, undermining result reproducibility. Regional supply chain differences also played a role - studies from North America reported higher CF values, likely due to more complete accounting of upstream forest operations. Greater methodological transparency is needed, especially in how biogenic carbon and production emissions are integrated.

5.4 BENCHMARKING AND SENSITIVITY INSIGHTS

Benchmarking against other reviews revealed that mean CFs for timber buildings (247.28 kg CO_2-eq m^{-2}) and EWPs (208 kg CO_2-eq m^{-3}) are aligned with prior studies. However, Australia reported the highest emissions due to extensive log haulage and energy-intensive harvesting. Material and transport choices significantly affect outcomes: low-density timber can reduce CF by up to 24%, and renewable energy systems cut emissions by up to 76%. Sawing and drying processes also contributed notably - air-drying timber showed four times lower emissions than kiln drying. These findings underscore the importance of supply chain optimisation.

5.5 DIRECTIONS FOR FUTURE RESEARCH

Future work should prioritise methodological standardisation, particularly in biogenic carbon modelling and system boundary definitions, to improve result comparability. Dynamic LCA models remain underutilised despite their ability to account for time-dependent carbon flows, EoL scenarios, and delayed emissions. Their wider adoption is needed, along with better integration of land-use change and carbon ownership tracking.

Additionally, EPDs must evolve to reflect both fossil and biogenic emissions transparently, using dynamic reporting methods where possible. Regional factors such as forestry practices, energy sources, and transport logistics must also be more systematically integrated into carbon accounting. Finally, greater focus is needed on circular timber strategies. Reuse of reclaimed timber can reduce emissions by up to 92%, but regulatory and economic barriers limit adoption. Research into modular design, material recovery, and reuse incentives could accelerate low-carbon construction.

6 - CONCLUSION

This study systematically reviewed 63 publications on carbon accounting of EWPs and timber buildings, focusing on the production stage (A1–A3). It found substantial variation in carbon footprint results across studies, driven by inconsistent system boundaries, functional units, database use, and carbon modelling approaches. While cradle-to-grave boundaries were most common, their definitions varied, and EPDs often lacked transparency in reporting biogenic carbon. CLT dominated the literature, but wider product diversity exists. Only four studies applied dynamic LCA, highlighting a gap in capturing temporal carbon dynamics.

To advance low-carbon timber construction, future research should focus on harmonising accounting methods, expanding dynamic LCA adoption, improving data traceability, and supporting reuse and circularity. Addressing these gaps is critical for positioning timber as a verifiable and scalable solution for climate-resilient construction.

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